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A review of power battery thermal energy management

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ABSTRACT

This paper reviews the development of clean vehicles, including pure electric vehicles (EVs), hybrid electric vehicles (HEVs) and fuel cell electric vehicles (FCEVs), and high energy power batteries, such as nickel metal hydride (Ni-MH), lithium-ion (Li-ion) and proton exchange membrane fuel cells (PEMFCs). The mathematical models and thermal behavior of the batteries are described. Details of various thermal management techniques, especially the PCMs battery thermal management system and the materials thermal conductivity, are discussed and compared. It is concluded that the EVs, HEVs and FCEVs are effective to reduce GHG and pollutants emission and save energy. At stressful and abuse conditions, especially at high discharge rates and at high operating or ambient temperatures, traditional battery thermal energy management systems, such as air and liquid, may be not meeting the requirements. Pulsating heat pipe may be more effective but needs to be well designed. In addition, progress in developing new high temperature material is very difficult. PCM for battery thermal management is a better selection than others. Nevertheless, thermal conductivity of the PCMs such as paraffin is low and some methods are adopted to enhance the heat transfer of the PCMs. The performance and thermo-mechanical behaviors of the improved PCMs in the battery thermal management system need to be investigated experimentally. And the possibility of the heat collection and recycling needs to be discussed in terms of energy saving and efficient.

Contents

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1. Introduction

As an important part of national economy, with high consumption of energy, especially petroleum resource, transportation industry has received much concern [1]. Under the pressure of energy shortage and environment pollution, automobile manufacturers are forced to shift their attention to green energy power and clean vehicles. Pure electric vehicles (EVs), hybrid electric vehicles (HEVs) and fuel cell electric vehicles (FCEVs) are more energy efficient and cleaner than conventional vehicles [2–17]. The improving electric vehicles market demands high specific power and high specific energy density batteries to meet the operational needs of electric vehicles [18]. Various batteries such as lead-acid, zinc/halogen, metal/air, sodium-beta, nickel metal hydride (Ni-MH) and lithium-ion (Li-ion) are available for EVs and HEVs, proton exchange membrane fuel cells (PEMFCs), for FCEVs. On the one hand, the performance of electric vehicles is determined by the batteries that the battery safety is a key issue for electric vehicles applications. On the other hand, the cost is a key barrier to the viability of the electric vehicles for both manufactures and customers. Therefore, improving the power performance and cycle life of the battery is very important.

Nevertheless, the power improvement of electric vehicles needs large-scale battery and high current discharge. These batteries generate much heat during rapid charge and discharge cycles at high current levels, such as during quick acceleration, with various chemical and electrochemical reactions [19–23]. The safety risks, overheating, combustion, and explosive, increase with the amount of thermal energy contained within the battery or pack [24]. In addition, excessive or uneven temperature rise in a module or pack reduces its cycle life significantly [25]. The performance of PEMFC depends obviously on the amount of water vapor, while the local dehydration or water condensation due to uneven temperature distribution can cause performance degradation [26]. In short, no matter whether a battery is of any type: lead-acid, Ni-MH, Li-ion and PEMFC, with effective heat dissipation and thermal runaway safety, all require a successful battery thermal energy management system.

Battery thermal energy management, including traditional cooling systems, such as an air thermal management system with an electric fan, liquid thermal management system with water, glycol, oil, acetone or even refrigerants, hear pipe thermal management system and PCM thermal management system have been investigated by many researchers. Thermal energy management for PEMFC also attracted more attention during the last decade. Single PCM is not sufficient for high heat fluxes, such as paraffin wax with large heat storage capacity but low thermal conductivity. To resolve the conflict between large heat storage capacity and low thermal conductivity, many methods have been investigated for increasing the thermal conductivity of PCMs. It is also important to get a stable and stronger battery module to withstand thermo-mechanical effects while in operation [27].

It may be mentioned that in the literatures that there are no comprehensive works on battery thermal management. This paper presents a review on the development of power batteries including the perspective of clean vehicles and power batteries, mathematical models of battery thermal behavior. Details of various thermal management methods, especially the PCMs battery thermal management system and the materials thermal conductivity, are discussed and compared. It is expected that this work will be useful for electric vehicle manufactures, researchers and others.

2. Transport energy saving and energy saving vehicle

2.1. Transport energy consumption and saving

The supply of energy is one of the great social challenges of the twenty-first century both at the global level and local level [28]. In recent years, energy shortage and environment pollution have become the critical problems faced by all countries throughout the world [29]. With economic development and vehicle sales growth, in many countries oil supply depends increasingly on import from other countries. For instance, according to data from the Chinese Customs Bureau, China imported 203.79 million tons of oil in 2009, accounting for nearly 52% of its total oil consumption in that year. Experts predicted that the data will reach 400 million tons and more than 70% in 2020, respectively. According to BP Statistical Review of World Energy 2010, although global oil consumption declined by 1.7%, it was still up to 3882.1 million tons. China's total oil consumption grew at a rate of 6.7% and reached 404.6 million tons, and its share of world total oil consumption was about 10.4%, in 2009 [30].

One of the sectors featuring the most fuel-consumption processes is transportation, typically covering 30–35% of the total fuel needs of most industrialized countries [31]. Globally, private transport was 95% dependent on oil, and it accounted for over 50% of the oil that the world consumed in 2007 [32]. Amjad et al. [5] also showed that the transportation is the most rapidly growing consumer of the world's energy, consuming 49% of the oil resources in a review paper published in 2010. To deal with the energy challenge in the transport sector, the first need is to save energy. Energy saving reduces the unnecessary final energy consumption which does not correspond to the production of utility and services [33].

On the other hand, large amounts of green house gases (GHG) and pollutants are emitted with the fossil fuels kindling. Baptista et al. [9] estimated actual yearly values of energy consumption and emissions of Portuguese by using COPERT software, which are presented in Table 1, including carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x) and particulate matter (PM). In United States, the transportation accounted for 28% of all greenhouse gas emissions, 34% of all carbon dioxide emissions, 36–78% of the main ingredients of urban air pollution, and 68% of all oil consumption [34].

For the purpose of energy saving and environment protection, people all over the world are striving to find new technology to improve energy efficiency and reduce GHG and pollutants emission. The Chinese government has created many energy policies to save energy [35]. Since 2001, anticipating fast growth of the Chinese automotive market and consequent large increase in oil consumption directed China to study the feasibility of developing Chinese automotive fuel consumption standards. It can be seen from Table 2 that the number of automobiles in China of 2010 is five times more than that of 2000. From 2004, the Chinese government has made and took effect on some fuel consumption limit standards for the purpose of reduced oil consumption and CO_2 emissions [36]. In the United States, there are many transportation policies such as

Table 1
Annual energy consumption and emissions of Portuguese.

Vehicle category	Energy consumption (l/100 km)	Emissions (kton)					
		TJ	CO_2	CO	HC	NO_x	PM
Gasoline <1.4 L	6.9	56,163	4058	112	15.7	16.0	0.0
Gasoline 1.4–2.0 L	8.2	15,223	1100	18	2.5	2.6	0.0
Gasoline >2.0 L	10.3	2150	155	1.2	0.14	0.15	0.0
Diesel <2.0 L	6.1	63,989	4724	5.8	0.94	20.0	2.1
Diesel >2.0 L	7.9	28,651	2115	2.9	0.83	7.1	1.0

reducing vehicle-mile traveled and vehicle resistance, improvement to conventional engine technology, transition to alternative low-carbon, non-petroleum based fuels and new high-efficiency power train [37]. Despite these, the efficiency of oil utilization in vehicles is still very low, and thus a great potential to improve the fuel efficiency.

2.2. Clean vehicles and the advantages

As the environment pollution is a serious social problem, automobile manufacturers are forced to shift part of their productions from pure internal combustion systems to new energy saving vehicles [7]. The proposed solution is to produce clean vehicles such as pure EVs, HEVs and FCEVs. Masayoshi [7] has estimated that electric systems would be widely used in the near future. Until now, many researchers have concluded that EVs, HEVs and FCEVs offer the best possibility for the use of new energy sources [2–17].

EV, first built in Britain by Robert Davidson in 1873, nearly 12 years earlier than the first gasoline-powered vehicle, consists of an energy source, a power converter, an electric motor and a mechanical transmission [38]. HEV is a type of hybrid electric vehicle which combines a conventional internal combustion engine propulsion system along with an electric propulsion system [39]. FCEVs using fuel cell as power system have high efficiency, low operation noise and little or no emissions from hydrogen or hydrogen-rich reformer gases and air, and the by-products are exhaust gases, water and waste heat [15].

In principle, the electricity used by EVs or the hydrogen used by FCEVs could be generated by clean and CO_2-free processes, using renewable sources such as solar energy or fossil energy with CO_2 capture and storage techniques [31,40,41]. Moreover, the EVs and FCEVs are the only potential zero-emissions-vehicle replacements for the internal combustion engine [16,42–44]. That is why they are often regarded as the long-term complete solution to the problem of pollution and energy shortage.

EVs and FCEVs create social benefits by generating power without polluting emissions, and HEVs by reducing gasoline combustion. Andersen et al. [32] have shown that, by using EVs instead of gasoline-consuming vehicles, GHG emissions would be reduced up to 20% and could be further up to 40% as the electric power generated from renewable sources. Chau et al. [38] have pointed out that the emissions due to the generation of electricity for EVs is only 2% in carbon monoxide, 76% in carbon dioxide, 56% in nitrogen oxides and 9% in hydrocarbons exhausted by gasoline powered vehicles. Baptista et al. [9] also indicated that using HEVs would emit less 20–40% CO_2 emissions than conventional vehicles. HyWays has concluded that, by 2050, if 80% of road vehicles were FCEVs this would result in 50% less CO_2 emissions [45]. Endo [46] analyzed the market penetration of FCEVs by using MARKAL to model an energy system of Japan. He concluded that the vehicle efficiency of the HEV would be improve to 36% in 2020 and then to be held constant at 36%, EV was assumed to be held constant at 80% and FCEVs were assumed to be 60–81% in 2020. These CO_2 emissions after 2030 will decrease rapidly owing to the high-efficiency, reaching two-thirds of the 1990 CO_2 emission level by 2050. Rosenberg et al. [47] also using MARKAL connection with an infrastructure model H2INVEST analyzed the market penetration of transport in Norwegian during the period 2005–2050. They showed that the introduction of HFCVs requires strong limitations on CO_2 emissions or high oil and gas prices. More details of performance parameters of gasoline and diesel versus EVs, HEVs and FCEVs vehicles are summarized in Table 3. The data predicted by different researches may not be exactly the same, but the views of them are consistent, that is the clean vehicles will be the only trend in vehicles market in the future.

2.3. The perspective of clean vehicles

Currently the barrier for private customer wide-spread adoption of EVs, HEVs and FCEVs is the high fuel cost. The assumptions of the fuel cost have been made by Offer et al. [45] are summarized in Table 4. The assumptions may be not very accurate, but it is assumed that the cost difference of hydrogen or electric and gasoline will become smaller. In addition, with the technologies of making hydrogen and generating electricity developing, the cost will also be reduced. All these will give impetus to private customers pay more attention on clean vehicles.

As gasoline-powered vehicles showed much better performance than EVs that received much attraction, the EVs developed very slowly until 1970s because of the energy crisis and oil shortage.

HEVs have received a large amount of attention from the media and analysts as green vehicles, which were first introduced in the United States in 1999, seven years later (in 2006), consumers in the United States purchased over 250 000 new HEVs, which represented 70% of global HEVs sales in that year [50]. The HEVs sales have significantly increased to 312 000 in 2008 [11]. FCEVs have offered a window of opportunity to change the relationship among the user, the energy providers and automotive industry [51]. HEVs were being imported to Korea in 2006. The number of new registrations for HEVs in 2008 was 637, compared with around 1.2 million new cars were registered in 2008, there is a great potential for the Koreans to develop clean vehicles [11].

Morgan has estimated that 11 million EVs could be sold worldwide by 2020. The United States announced upwards of $2.5 billion United States of funding and grants for a variety of EV-related companies and China is also focusing on the EV from the perspective of economic and energy policy [52]. Rosenberg et al. [47] indicated that the HFCV market share could grow to 50% by 2030 and 90% by

Table 2
The number of automobiles in China.

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Million	16.08	18.02	20.53	24.30	27.42	31.60	49.85	56.97	64.67	69.62	90.86

Table 3
Performance parameters of different vehicles.

	Reference(s)	Battery used	Capacity	Energy efficiency	W/kg 95% efficiency
Gasoline	[79]			15–20%	
Diesel	[79]			18–24%	
HEV	[48]	Lead-acid	25 A h		77
		Ni-MH	6.5, 12 A h		207, 195
		Li-ion	12, 4 A h		256, 745
	[79]			36%	
	[11]			64–87%	
EV	[49]	Li-ion (57V)	106 A h	95%	
		Silver-zinc (48V)	126 A h	81%	
	[48]	Li-ion	41, 90 A h		90, 255
		Lead-acid	60 A h		47
		Ni-MH	65, 85 A h		46, 40
	[79]			80%	
FCEV	[79]			60–81%	

Table 4
Summary of the running cost: 2010–2030.

Fuel cost	2010 ($G J^{-1}$)	2030 Optimistic ($G J^{-1}$)	2030 Pessimistic ($G J^{-1}$)	2030 Average ($G J^{-1}$)
Gasoline	$12.7	$19	$38	$28.5
Hydrogen	$42	$14	$56	$35
Electric	$36	$27	$45	$36

2050. Keles et al. [53] discussed the market penetration of FCEVs in Germany by using System Dynamics model and indicated that FCEVs will reach one-third of all passenger cars in 2040 and even two-third in 2050 with adequate financial supporting. The above perspective and more specific description can be seen in Table 5.

Where, "50% (2034)" means that HEVs will reach 50% market share of new cars sold by 2034. "50% (2042)" means that HEVs and FCEVs will reach 50% market share of new car sales market share by 2042. "50% (2045)"means that FCEVs will reach 50% market share of new car sales market share by 2045. "2/3 (2050)" means that FCEVs will reach about two-thirds of total market by 2050 if obtain a 4.8 billion Euros financial supporting. "50% (2020)" means that EVs and HEVs reach 50% market share of new car. Others mean that EV, HEVs and FCEVs will reach related proportion of total vehicles.

3. Power battery and thermal behavior

3.1. Power battery for electric vehicles

There are numerous rechargeable power batteries for EVs and HEVs such as lead-acid, nickel-based, zinc/halogen, metal/air, sodium-beta and Li-ion [38]. The power battery is by far the largest cost item and a key barrier to the viability of the battery-powered electric vehicles [37,60].

At the beginning of the 1990s, the lead-acid battery was available for consideration in electric vehicles because of promising cost and specific-power characteristics [61]. As lead-acid battery has a very poor cycle-life, some methods and funding were sought to develop improved cycle-life performance [61–63]. In 2000, the UK Foresight Vehicle Programme started with the objective of developing an optimized lead-acid battery as a solution for HEVs [6].

The market acceptability of lead-acid has been limited for battery EVs, prompting active development of higher-specific energy batteries. Ni-MH batteries are rapidly becoming the new choice for the emerging electric vehicle market [64,65]. Ni-MH battery become incumbent power to HEV incumbent is due to its comparatively high specific power, energy and life cycle [66].

Li-ion battery, provides longer cycle life, high energy and power, and higher voltages, of which three times that for Ni-MH batteries and two times that for lead-acid batteries have been commercially

Table 5
The perspective of clean vehicles.

	Reference(s)	EVs (million)	HEV s(million)	FCEVs (million)	Funding (billion)
Worldwide	[52]	11 (2020)			
	[34]		50% (2034) 50% (2042)	50% (2045)	
	[47]			200 (2050)	
US	[52]	1 (2015)	1 (2015)		$2.5
	[34]			0.765 (2020)	
	[4]				
China	[54]				$1.46
	[55]	5 (2020, including all clean vehicles)			
Canada	[56]	0.5 (2018)			
Japan	[79]			20% (2030)	
	[57]	50% (2020)			
Germany	[53]			2/3 (2050)	0.48 (Euros)
	[58]	1 (2020)			0.5 (Euros)
UK	[59]				0.25 (Pound)

used for a number of years since its invention by a Japanese company in 1991 [67–73,49,74–77]. Last year, Kojima et al. [78] have developed an elliptic Li-ion battery for fuel cell HEV application achieved a specific energy of 83 W h kg^{-1}, and with a specific power output of 3380 W/kg at 50% state of charge for 10 s. They also concluded that introduction of a Li-ion battery into the fuel cell HEV definitely suggested a reduced fuel consumption to 2/3. To meet the very high standards in terms of performance and service life, Li-ion batteries will also be able to play an important role in the EVs and HEVs market in the future.

The typical characteristics of EVs and HEVs power batteries of some experts studied are shown in Table 6. It can be seen that the Li-ion batteries have a better performance in terms of energy and power than others. Moreover, most of researchers are fairly optimistic about achieving a higher cycle performance with Li-ion battery.

Now the cost of Li-batteries is still very high compared with others. Baker et al. [82] have indicated that reducing the cost of Li-ion batteries from $384 to $200/kW h may lead to an overall reduction in the annual cost of abatement of $100 billion in the year 2050. Anyway, the future development of the battery-powered vehicles industry will greatly influence the advancement of long life, fast charging and large capacity batteries [83].

Fuel cell, first invented by Sir William Grove in 1843, is an advanced power for the future that is sustainable, clean and environmental friendly [84]. The fuel cell is generally classified into six types: alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC), direct methanol fuel cell (DMFC) and proton exchange membrane fuel cell (PEMFC) (also named as solid polymer fuel cell, SPFC) [38,84,85]. Chau et al. [38] summarized the typical characteristics of these fuel cells in Table 7. Among the various fuel cell types, MCFC and SOFC, with operating temperatures higher than 600 °C, are not considered for FCEVs.

3.2. Market penetration of power batteries

In the past two decades, the center of the international lead market has shifted to China. The output of raw and refined lead accounts for more than 30% of the world total [86]. In 2009, the output of lead in China reached 3.7 million tons. Simultaneously, total battery market in China was valued at $12.4 billion in 2006, 30.5% of which is lead-acid, 4.6% is Li-ion and Ni-MH [24]. According to the analysis above, continue to develop lead-acid is violate with the concept of green energy.

At the same time, Ni-MH batteries are too expensive, too heavy and bulky to be regarded as a long-term solution [37]. Researchers agreed that Li-ion batteries appear to be one of the most promising technologies for the mid-term requirements of EVs and HEVs [87,7]. Many signs show that the PEMFC will be the best choice of the future for application in FCEVs with the international law on green house gases control and the national renewable energy policy [84,88–90]. The perspective of clean vehicles in Table 5 is also strongly confirmed this view.

The rechargeable battery market will rise to $51 billion by 2013, which accounted for 4.2% will be shared by Ni-MH and Li-ion batteries [91]. The market for Li-ion transportation batteries will grow to nearly $8 billion dollars by 2015 [92]. The China Market Intelligence Center (CMIC) recently released that global automotive fuel cell market would increase to 10 billion dollars in 2013 [93]. By 2020, the Japan fuel cell market would increase to 11.1 billion dollars. In short, Ni-MH batteries as short and medium-term selection, Li-ion batteries as medium-term and fuel cells as long-term selection, are all will obtain more and more attention and improvement.

3.3. Battery safety and thermal behavior

Kitoh and Nemoto [94] emphasized that battery safety is a key issue for EVs and HEVs applications because a number of cells are installed inside. Many practical problems, however, have been encountered in development of Li-ion batteries mainly that include poor cycle performance and poor safety characteristics [95]. During battery charge/discharge, various chemical and electrochemical reactions take place. Selman et al. [19] have indicated that the temperature increase in the scaled-up cells is a major concern when the cells are operated at high discharge rates in their preliminary works. The batteries generate much more heat during rapid charge and discharge cycles at high current levels, such as during quick acceleration [20–23,96]. The improvement of battery-powered vehicles needs large-scale battery; however, with the size increasing and large packages forming, serious thermal stability problems will de posed [97,98]. EV Global Motors Company had announced the recall of 2000 batteries in their electric bicycles because of potential overheating in 2002 [99]. The safety risks such as overheating, combustion, and explosive increase with the amount of thermal energy contained within the battery or pack [24].

The performances of EVs, HEVs and HEVs are very dependent on power batteries [100]. It is very important to know the mechanism of the degradation of the batteries performance in high temperature and high discharge current. In Li-ion battery, heat may generate in the solid electrolyte interface (SEI) film [101–103], electrolyte and anode decomposition [104–110], the reaction of cathode and electrolyte [103,111], the reaction of cathode and adhesive [104,112,113]. The internal temperature of the Li-ion battery during overcharge was found to be as high as 199 °C, which is 93 °C higher than that on the surface [114].

Assuming a binary electrolyte and neglecting the enthalpy of mixing and phase change effects, the heat generation over all reactions term can be expressed as [115]

$$q = \sum_j \alpha_{sj} i_{nj} (\phi_s - \phi_e - U_j) + \sum_j \alpha_{sj} i_{nj} T \frac{\partial U_j}{\partial T} + \sigma^{eff} \nabla\phi_s \nabla\phi_s + k^{eff} \nabla\phi_e \nabla\phi_e + K_D^{eff} \nabla \ln\ c_e \nabla\phi_e \quad (1)$$

where α_{sj} is interfacial surface area per unit volume (cm^2/cm^3); i_{nj} is transfer current density (A/cm^2); ϕ_s is potential in the matrix phase (V); ϕ_e is potential in the solution phase (V); U_j is equilibrium potential (V); T is temperature (K); and σ_{eff} is effective matrix conductivity ($\Omega^{-1}\ cm^{-1}$); C_e is concentration of the electrolyte (mol/cm^3).

The heat produced at the positive electrode is about even three times more than that of overall battery [116]. Excessive local temperature rise may also cause reduction of cycle life and thermal runaway [25]. The characteristics of few commercially produced power batteries are summarized in Table 8 [117]. In terms of cycles 1000 and more cycles at 80% depth of discharge are expected in EV [76]. To achieve a good balance between performance and life, the best operating temperature for lead acid, Ni-MH and Li-ion batteries ranges between 25 and 40 °C, and temperature distribution from module to module is below 5 °C [118]. As temperature above 50 °C will lower the charging efficiency or lower the longevity properties, heat control is an important issue for Ni-MH, Li-ion and other batteries [119]. Sarre et al. [68] found that after a period of 22 months on high energy, cell energy and power were quite stable at 20 °C and showed 4% loss at 40 °C. Wu et al. [120] found that capacity of a fresh Li-ion battery at 3C discharge was decreased from 800 mAh to merely 20 mAh after storing at 60 °C. Saito et al. [121] studied the heat generation behavior of a Li-ion battery (US 14500, Sony Energytec) from 10 to 60 °C, and concluded that the heat generation was least at about 27 °C. Ramadass et al. [122] did a complete capacity fade analysis and elucidated that after 800 cycles cells cycled at

Table 6
Typical characteristics of EVs and HEVs power batteries.

	Reference(s)	Specific energy (Wh/kg)	Energy density (Wh/L)	Specific power (W/kg)	Cycle life (cycles)
Lead-acid	[38]	30–50	60–100	200–400	400–600
	[62]	48			800
Ni–Fe	[38]	30–55	60–110	25–110	1200–4000
Ni–Zn	[38]	60–65	120–130	150–300	100–300
Zn–Air	[38]	230	269	105	–
Ni-MH	[65]	80		1000	
Li-ion	[79]	93	114	350 (50%)	
	[80]	94.8			4000
	[65]	120–130	200–300	1500	
	[70]	150	300		1000
	[81]	150–200	460–600		8–10 years

Table 7
Typical characteristics of fuel cells.

	AFC	PAFC	MCFC	SOFC	DMFC	PEMFC
Fuel efficiency (%)	40–50	40–45	45–50	45–50	30–40	45–50
Power density (kW/m^2)	2–3	2–2.5	1–2	2.4–3	1.5–3.2	3.5–6
Working temperature (8 °C)	60–80	180–210	600–700	900–1000	<100	50–100
Projected cost (US$/kW)	>200	1000	1000	1500	>200	>200
Lifetime (kh)	>10	>40	>40	>40	>10	>40
For FCEVs			Difficult	Difficult		Good

50 °C lost more than 60% of initial capacity after 600 cycles and 70% after 500 cycles at 55 °C.

In general, temperature affects the battery performance including: (i) electrochemical system; (ii) round trip efficiency; (iii) charge acceptance; (iv) power and energy capability; (v) reliability; (vi) cycle life and cost [118]. In 1990s, researchers had realized the importance of battery safety concerning heat accumulation and studied for effective battery thermal energy management [21,123–126]. Effective heat dissipation and thermal runaway safety, which would require a successful thermal energy management, are still the major concerns in the commercialization of Li-ion batteries [19,117,127].

On the material side, many researches were focused primarily on development new anode and cathode materials, electrolytes and flame retardant materials. Kise et al. [71,128] proposed a new electrode to improve the high temperature safety of Li-ion battery. Yoshizawa and Ikoma [129] synthesized lithium magnesium cobalt oxide with thermal stability for high safety lithium-ion batteries. Arai et al. [130] investigated high temperature stable lithium salt ($Li_2B_{12}F_{12}$) for Li-ion batteries and studied mainly on temperature performance, cycle life and storage life at 60 °C. Kohno et al. [131] presented aluminum-laminated Li-ion battery and Lackner et al. [132] did studies on small plastic Li-ion battery. Ma et al. [133] studied Fe-doped $Li_2Ti_3O_7$ ramsdellite for lithium ion batteries and cycled at 70 °C. Ravdel et al. [134] suggested that preventing transesterification of dialkylcarbonates should inhibit thermal decomposition of LiPF6/carbonate based electrolytes. Bott et al. [135] studied $LiPF_6$-EC: EMC electrolyte for Li-ion batteries. For the same purpose, flame retardant was explored widely [136–139]. Maleki et al. [140] suggested high thermal conductivity negative electrode material to design high thermal conductivity Li-ion cells.

Earlier researches were focused on the effects of the electrochemistry parameters on the performance of the PEMFC [141,142]. The thermal behavior of the PEMFC and the temperature distribution effect were not a major concerns. Recently, the large scale FCEVs are required with the FCEVs improvement. Thus thermal behavior and heat transfer within the PEMFCs attract more attention [26,143–150].

4. Battery thermal energy management

4.1. Methods

Based on the above analysis, there are two main problems caused by temperature. The first is that the high temperature during charge and discharge will lead to the possibility that temperatures will exceed permissible levels and decrease the battery performance. Another is that the uneven temperature distribution in the battery pack will lead to a localized deterioration. Thereof, temperature uniformity, within a cell and from cell to cell, is important to achieve maximum cycle life of cell, module, and pack [151]. To optimize the performance of a battery and pack/module, the thermal energy management system should have [152–154].

(i) Optimum operating temperature range for every cell and all battery modules, rejecting heat in hot climates/adding heat in cold climates.
(ii) Small temperature variations within a cell and module.
(iii) Small temperature variations among various modules.
(iv) Compact and lightweight, easily packaged, reliable, low-cost and easy for service.
(v) A provision for ventilation if the battery generates potentially hazardous gases.

The thermal management system may be passive (i.e., only the ambient environment is used) or active (i.e., a built-in source

Table 8
Characteristics of few commercially power batteries.

	Ni-MH	Lead-acid	Li-ion	Li-ion polymer
Cycle life (to 80% of initial capacity)	300–500	200–300	500–1000	300–500
Overcharge tolerance	Low	High	Very low	Low
Self-discharge/month	30%	5%	10%	∼10%
Operating temperature (discharge)	−20 to 60 °C	−20 to 60 °C	−20 to 60 °C	0 to 60 °C

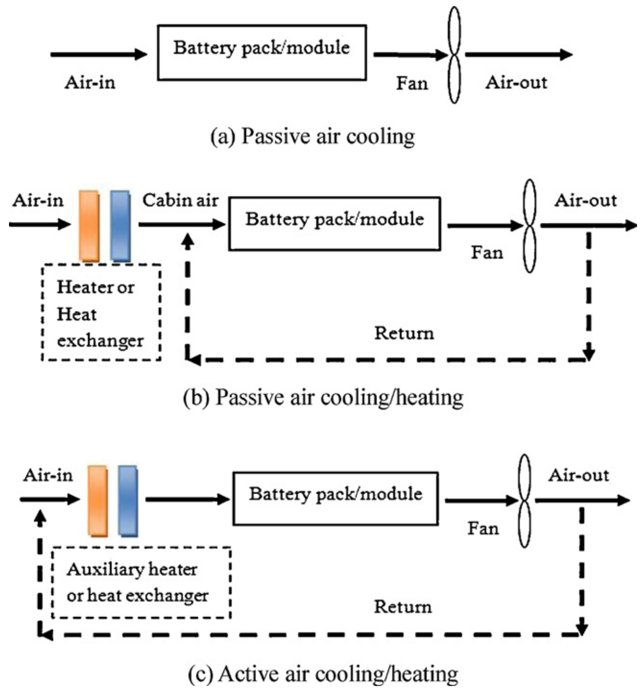


Fig. 1. Thermal management using air.

provides heating and/or cooling), and can be also divided into four categories based on medium [25,153–155].

(i) Air for heat/cooling/ventilation (Fig. 1).
(ii) Liquid for cooling/heating (Fig. 2).
(iii) Phase change materials (Fig. 3).
(iv) Combination of above.

4.2. Numerical models and simulation

There are many methods to analyze the battery thermal behavior and thermal management effect, in which experimental and numerical simulations are the most popular. Computational fluid dynamics (CFD) [156,157] and finite element methods (FEM) [158] are recommended for the investigation of the thermal systems. Advanced mathematical/numerical models play an important role in simulations. In this section, we review the scientific literature on numerical models of battery thermal behavior. Based on this, our skills in specific solving process, the energy balance equation and boundary condition equation are summarized in the tables.

Mathematical/numerical models of battery thermal behavior (Thermal model) were used for the optimum thermal energy management designing of the systems for automotive applications. The equations of the thermal models should be based on [159]

(i) Energy balance equation.
(ii) Heat generation equation, simplified/complex.
(iii) Boundary condition equation, linear/nonlinear, conductive/convective/radiated.

Many thermal models were developed to describe temperature profiles and time evolution of temperature [160]. Catherino [161] performed a model to attempt studying the thermal runaway effect in lead-acid batteries. Inui et al. [162] simulated two-dimensional and three-dimensional temperature distributions in cylindrical and prismatic Li-ion batteries. Chen et al. [163] developed a detailed three-dimensional thermal model to examine the thermal behavior of Li-ion batteries. In Chen's model, the layer-structured core

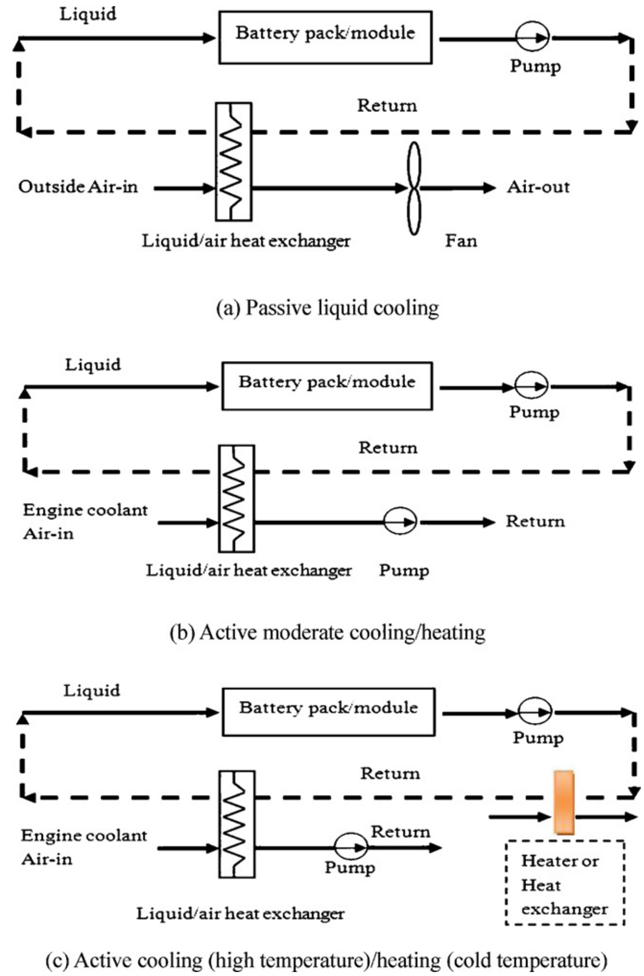


Fig. 2. Thermal management using liquid.

region, the contact layer and the battery case are all considered and the location-dependent convection and the radiation included simultaneously to enhancing the accuracy at the boundaries.

The lumped capacitance battery thermal model initially developed at National Renewable Energy Laboratory (NREL, US) by Steve Burch and updated later by Valerie Johnson is shown in Table 9 [71].

The subscript "ess" means energy storage system.

Al-Hallaj [164] used a simplified one-dimensional thermal mathematical model with lumped parameters to simulate temperature profiles inside cylindrical Li-ion (Sony, US18650) cells, which can be summarized in Table 10. Forgez et al. [165] also developed a

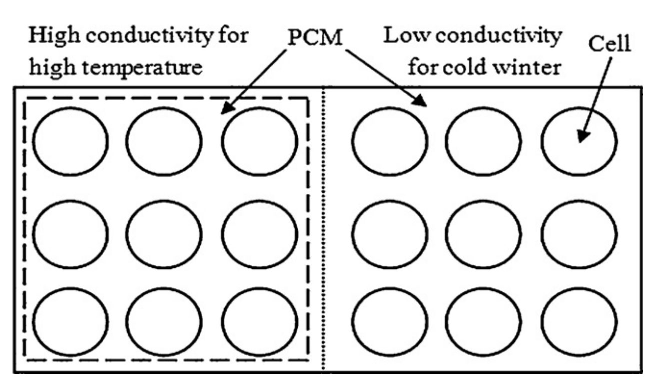


Fig. 3. Thermal management using PCM.

Table 9
Lumped capacitance thermal model.

$Q_{ess_case} = \frac{T_{ess}-T_{air}}{R_{eff}}$	Q_{ess_case}	Heat dissipated
	T_{ess}	Battery temperature
$R_{eff} = \frac{1}{hA} + \frac{t}{kA}$	T_{air}	Surrounding temperature
	R_{eff}	Effective thermal resistance
$h = \begin{cases} h_{forced} = a\left(\frac{m/\rho A}{5}\right)^{b}, & T_{ess} > ess_set_tmp \\ h_{nal} = 4, & T_{ess} > ess_set_tmp \end{cases}$	h	Heat transfer film coefficient
	k	Heat conductivity coefficient
	ess_set_tep	A set temperature
$T_{air} = T_{amb} + \frac{0.5Q_{ess_case}}{m_{air}c_{p,air}}$	m_{air}	Air flow rate
	$c_{\rho,air}$	Air heat capacity
$T_{ess} = \int_0^t \frac{Q_{ess_gen}-Q_{ess_case}}{m_{ess}c_{p,ess}}dt$	Q_{ess_gen}	Heat generated
	m_{ess}	Battery mass
	$c_{\rho,ess}$	Battery heat capacity

Table 10
Simplified one–dimensional thermal mathematical model.

Energy equation	$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{q}{k_{cell}} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$	R	Radial distance (mm)
		q	Heat generation rate (W L^{-1})
Boundary conditions	$\left.\frac{dT}{dr}\right\|_{r=0} = 0$	k_{ell}	Thermal conductivity (W m^{-1} K^{-1})
	$-k_{cell}\left.\frac{dT}{dr}\right\|_{r=R} = h(T - T_a)$	α	Thermal diffusivity (m^2 s^{-1})
		t	Time (s)
		R	Cell radius (mm)
The initial condition	$T = T_a$ at $t = t_0$ and for all r	T_a	Ambient temperature (K)
The governing thermodynamic relations	$Q = \Delta G + T\Delta S + W_{el}$	t_0	Initial time (s)
	$\Delta G = -nFE_{eq}$	Q	Overall heat generation (J)
	$W_{el} = -nFE$	G	Gibbs free energy (J mol^{-1})
	$Q' = I\left[(E_{eq} - E) + T\frac{dE_{eq}}{dT}\right]$	S	Entropy (J mol^{-1} k^{-1})
		W_{el}	Electric work (J)
		n	Number of electrons
		F	Faraday's constant
		E	Cell voltage on load (V)
		Q'	Overall heat generation rate (W)
		E_{eq}	Cell equilibrium voltage (V)

thermal model of a cylindrical $LiFePO_4$/graphite lithium-ion battery with lumped parameter to estimate the temperature response.

Smith and Wang [166] used a complex one-dimensional thermal mathematical model with lumped parameters. Their model can be summarized in Table 11. The details of the electrochemical model parameters can be seen in Ref. [166].

Wu et al. [167] used a two-dimensional, transient heat-transfer model to simulate the temperature distribution, which is shown is Table 12.

Kim et al. [168] formulated a three-dimensional thermal abuse model for Li-ion cells. The model can be summarized in Table 13. The more detailed physical and kinetic parameters used for abuse simulations can be seen in Ref. [168]. This model emphasises more on the thermal abuse behavior especially on thermal chemistry mechanism. Lee et al. [169] used a three-dimensional model to investigate the effects of operating and ambient conditions on the thermal behavior furthered their study on a 42-V automotive electrical system.

In the near future, Guo et al. [170] also developed a three-dimensional thermal model for analyzing the temperature distribution under abuse conditions; different from Kim's model, they took into account the effects of heat generation, internal conduction and convection, and external heat dissipation. The geometrical features were also considered. The total heat generation Q was same as that in Table 10. The equations they used for the calculation of temperature field can be written as

$$[C]\{T\} + [K]\{T\} = [Q] \quad (2)$$

where $[C]$ is the global thermal capacity matrix; $[K]$ denotes the global matrix of heat conduction; $\{T\}$ represents the global nodal temperature array; and $[Q]$ is the global temperature load array.

4.3. Air for thermal management

The battery pack design with different cell configurations used commonly is shown in Fig. 4 [171]. Considering the use of air for battery thermal management may be the simplest approach, and air cooling systems are used for these vehicles because of cost and space limitations [100].

The shape of the battery pack is regular that there are usually two ways for the air to flow over the battery, which can be seen in Fig. 5.

It is apparent that the air natural convection for battery dissipation is invalid; heat transfer with air is achieved by directing/blowing the air parallel or serial across the battery module/pack. The Toyota Prius supplies conditioned air from the cabin as thermal management for cooling the batteries. Zolot et al. [172] used a parallel airflow scheme in a Toyota Prius hybrid electric

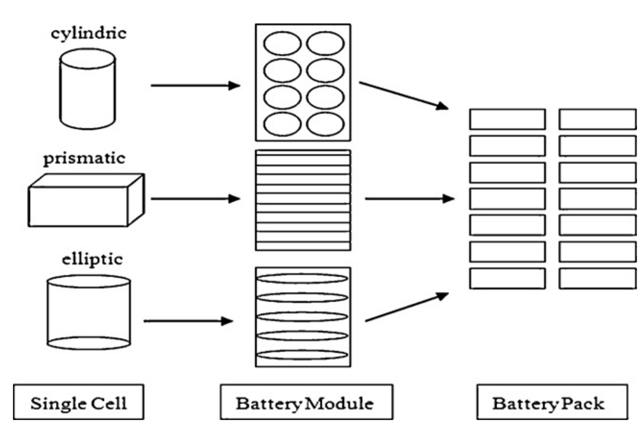


Fig. 4. Schematics of the battery pack design with different cell configurations.

Table 11
One-dimensional thermal mathematical model.

Conservation equations		Boundary conditions
Species, electrolyte phase	$\frac{\partial \varepsilon_e C_e}{\partial t} = \frac{\partial}{\partial x}\left(D_e^{eff}\frac{\partial}{\partial x}C_e\right) + \frac{1-t_+^0}{F}j^{\mathrm{Li}}$	$\frac{\partial c_e}{\partial x}\Big\vert_{x=0} = \frac{\partial c_e}{\partial x}\Big\vert_{x=L} = 0$
Species, solid phase	$\frac{\partial c_s}{\partial t} = \frac{D_s}{r^2}\frac{\partial}{\partial x}\left(r^2\frac{\partial c_s}{\partial r}\right)$	$\frac{\partial c_s}{\partial r}\Big\vert_{r=0} = 0,\ -D_s\frac{\partial c_s}{\partial r}\Big\vert_{r=R_s} = \frac{j^{Li}}{\alpha_s F}$
Charge, electrolyte phase	$\frac{\partial}{\partial x}\left(k^{eff}\frac{\partial}{\partial x}\phi e\right) + \frac{\partial}{\partial x}\left(k_D^{eff}\frac{\partial}{\partial x}\ln c_e\right) + j^{\mathrm{Li}} = 0 + \frac{\partial \phi e}{\partial x}\Big\vert_{x=0} = \frac{\partial \phi e}{\partial x}\Big\vert_{x=L} = 0$	
Charge, solid phase	$\frac{\partial}{\partial x}\left(\sigma^{eff}\frac{\partial}{\partial x}\phi s\right) + j^{\mathrm{Li}}$	$-\sigma_-^{eff}\frac{\partial \phi_s}{\partial x}\Big\vert_{x=0} = -\sigma_+^{eff}\frac{\partial \phi_s}{\partial x}\Big\vert_{x=L} = \frac{I}{A}\frac{\partial \phi_s}{\partial x}\Big\vert_{x=\delta-} = \frac{\partial \phi_s}{\partial x}\Big\vert_{x=L-\delta_+} = 0$
Electrochemical kinetics Reaction rate	$j^{\mathrm{Li}} = \alpha_s i_o\left\{\exp\left[\frac{\alpha_a F}{RT}\left(\eta - \frac{R_{SEI}}{\alpha_s}j^{\mathrm{Li}}\right)\right] - \exp\left[\frac{\alpha_c F}{RT}\left(\eta - \frac{R_{SEI}}{\alpha_s}j^{\mathrm{Li}}\right)\right]\right\}$	
Over potential		$\eta = \phi_s - \phi_e - U$
Effective properties Electrolyte ionic diffusivity		$D_e^{eff} = D_e\varepsilon_e^p$
Electrolyte ionic conductivity		$k^{eff} = k\varepsilon_e^p$
Electrolyte ionic diffusional conductivity		$k_D^{eff} = \frac{2RTk^{eff}}{F}(t_+^0 - 1)\left(1 + \frac{\mathrm{d\ ln\ f_+}}{\mathrm{d\ ln\ c_e}}\right)$
Solid phase electronic conductivity		$\sigma^{eff} = \varepsilon_s\sigma$
Specific interfacial surface area		$\alpha_s = \frac{3\varepsilon_s}{r_s} = \frac{1-\varepsilon_e-\varepsilon_{sp}-\varepsilon_f}{r_s}$

Table 12
Two-dimensional transient heat-transfer model.

Energy equation	$\rho C_p\frac{\partial T}{\partial t} = k_r\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + kz\frac{\partial^2 T}{\partial z^2} + q$	C_p k_r	Average heat capacity "k" in r direction
The rate of heat generate	$q = \frac{I}{v_b}\left[(E_o - E) + T\frac{dE_o}{T}\right]$	k_z	"k" in z direction
Boundary conditions	$\frac{\partial T}{\partial t} = 0, r = 0, 0 < z < Z - k_r\frac{\partial T}{\partial r} = h_r(T - T_\infty), r = R, 0 < z < Z$ $\frac{\partial T}{\partial t} = 0, r = 0, 0 < z < Z - k_r\frac{\partial T}{\partial r} =$ $h_r(T - T_\infty), r = R, 0 < z < Z$ $-k_z\frac{\partial T}{\partial z} = h_z(T - T_\infty), z = 0, 0 < r < R$ $-k_z\frac{\partial T}{\partial z} = h_z(T - T_\infty), z = Z, 0 < r < R$	V_b I E_o T_∞ R Z h_0	Volume of battery Current Open-circuit potential The ambient Temperature Radius of the battery Height of the battery Average "h"
Boundary conditions	$\int\int qdA = h_0\eta_0 A_t[\bar{T}_s - \bar{T}_f], r = R$	η_0	Overall efficiency of the metallic fin
The initial condition	$T = T_\infty, t = 0, 0 < r < R, 0 < z < Z$	A_t	The total area average surface, film
		$T_s T_f$	

vehicle, to cool the battery (also used for heating). The forced air system consists of two vents, one for cabin air to return and another to supply outside air. Lou [173] designed a cinquefoil battery pack constituted by 5 long modules (total voltage is 36 V) to enhance the heat transfer for Ni-MH batteries, which is shown in Fig. 6. The experiment showed that the temperature drop was fixed to the expectant target, but the temperature difference was still higher by 5 °C. In addition, the structure of this battery pack was very complex. The cells nearly the fan (3a) would appear a larger temperature drop than far from the fan (3b) that the temperature would distribute uneven.

Air forced convection cooling could mitigate temperature rise in the battery. If the battery temperature rises higher than 66 °C, it would be difficult to cool it to below 52 °C by air-cooling [174].

Table 13
Three-dimensional thermal abuse model for Li-ion cells.

Energy equation	$\frac{\partial(\rho c_p T)}{\partial t} = -\nabla(k\nabla T) + S$	ρ c_p	Density ($\mathrm{g\,cm^{-3}}$) Heat capacity ($\mathrm{J\,g^{-1}\,K^{-1}}$)
Heat source	$S = S_0 + S_{joul} + S_{combustion} + \ldots$	T	Temperature (K)
Heat generation	$S_0 = S_1 + S_2 + S_3 + S_4 + S_5$	H_i	Specific heat release ($\mathrm{J\,g^{-1}}$)
S_1:	$S_i = H_i W_i R_i, i = 1, 2, \ldots$	W_i	Volume-specific ($\mathrm{g\,m^{-3}}$)
SEI decomposition	$R_i = A_i\ \exp\left[-\frac{E_{a,i}}{RT}\right]c_i^{m_i}, i = 1, 4, 5;$	R_i	Reaction parameters
S_2: negative/electrolyte	$\frac{dc_i}{dt} = -R_i,\quad i = 1, 2, 4, 5,\ \frac{d\alpha}{dt} = R_3$	$E_{a,i}$ A_i	Reaction parameters Reaction parameters
S_3: positive/electrolyte	$R_2 = A_2\ \exp\left[-\frac{t_1}{t_{1,ref}}\right]c_2^{m_{2,1}}\exp\left[-\frac{E_{a,2}}{RT}\right]$	c_i α	Dimensionless amount Degree of conversion
S_4: electrolyte decomposition	$R_2' = A_2\left[-\frac{t_{1,ref}}{t_1}\right]c_2^{m_{2,1}}\exp\left[-\frac{E_{a,2}}{RT}\right]$	t_i T_{surf}	Dimensionless measure Surface temperature
S_5: negative/binder	$R_3 = A_3\alpha^{m_{3,1}}(1-\alpha)^{m_{3,2}}\exp\left[-\frac{E_{a,1}}{RT}\right]$	T_{am} ε σ	Ambient temperature Emissivity Stefan–Boltzmann constant
Convective	$q''_{conv} = h(T_{surf} - T_{am})$		
Radiation	$q''_{radi} = \varepsilon\sigma(T_{surf}^4 - T_{am}^4)$	q''	Heat flux

R^2: tunneling regime; R'^2: diffusion regime.

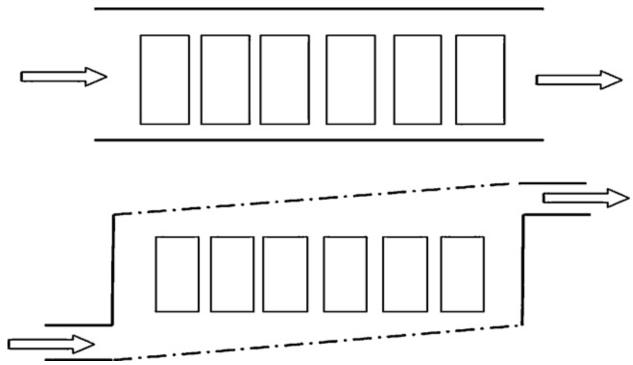


Fig. 5. Air flow over the battery.

Furthermore, at stressful and abuse conditions, especially at high discharge rates and at high operating or ambient temperatures (>40 °C), air-cooling will not be proper, and the non-uniform distribution of temperature on the surface of the battery becomes inevitable [167].

The batteries such as Li-ion batteries have high power density, but their power is severely limited at −30 °C [175]. If the battery is operated at a very low temperature such as −30 °C in cold winter, the battery must be heated rapidly after a cold startup. In Nelson et al. [174] study, they noted that for a 25 kW delivering power, only 5 kW could be supplied by the battery at −30 °C. But the battery could not heat itself that rapidly with I^2R heating. In this case, heating the battery must be considered. They also suggested two ways to rapid heating: (i) with electric heaters within the battery, (ii) by heating the battery coolant with heat transferred from the engine coolant. As the air is difficult to heat the battery rapidly, then we can consider liquid such as water, which has a higher conductivity than air, for battery thermal management.

4.4. Liquid for thermal management

Most of the past studies showed that the heat dissipation could not be significantly alleviated by air natural or forced convection, particularly in large-scale batteries [176]. The battery thermal management system using liquid could be achieved either through discrete tubing around each module; with a jacket around the module; submerging modules in a dielectric fluid for direct contact; or placing the modules on a liquid heated/cooled plate (heat sink) [153]. The heat transfer medium could be water, glycol, oil, acetone or even refrigerants.

Pesaran [153,154] discussed the performance of liquid cooling versus air cooling, cooling and heating versus cooling only systems. With the experiment results, he suggested that using air as the heat transfer medium is less complicated, though less effective, than a system using liquid cooling/heating. For parallel HEVs, air is adequate, whereas for EVs and series HEVs, liquid might be required. Recently (in 2010), Pendergast et al. [177] used the Panasonic (CGR18650E) cells and housed them inside a triangular aluminum module, then put them under water. Their experiment can be also seen as a simple water-cooling battery thermal management. In our previous work, we also designed a liquid thermal management for battery module and pack with efficient and easy recycling functions, which can be seen in Ref. [178]. Seal is very important to prevent liquid leak that the manufacturers do not want to use liquid for battery thermal management.

Heat pipe, which makes use of change-of-phase heat transfer, first suggested by R.S. Gaugler in 1942, has been taken more attention recent years. It consists of a sealed container whose inner surfaces have a capillary wicking material to provide driving force to return the condensate to the evaporator. As the liquid is used to complete the phase change process, heat pipe is thought to be liquid for battery thermal management in this paper. In Wu et al. [167], two heat pipes with metallic aluminum fin were attached to the battery (Li-ion, 12 A h, cylindrical, 40 mm in diameter, 110 mm in length) wall to mitigate the temperature rise. Their experimental and simulation (Table 12) results showed that the heat pipe significantly reduced the temperature rise, especially with the help of metallic aluminum fin. Jang and Rhi [179] adopted a loop thermosyphon (similar to heat pipe) cooling method for high efficiency cooling. The system combined the heat pipe and air cooling; the heating section distributed on the surface of the battery and the fan blew the air flow over the condenser section. Their experiment showed that the operating temperature was under 50 °C with pure water as medium and 45 °C with acetone.

Swanepoel [180] did a lot of works in his thesis for the degree M. Sc. in Engineering. He designed pulsating heat pipe (PHP) for the purpose of the Optima Spirocell (12 V, 65 A h) lead acid batteries thermal management and control of HEV components. The closed loop PHP is shown in Fig. 7. To investigate of the feasibility of using PHP technology for the battery thermal management of HEVs, he positioned the batteries in the boot of the HEV, which is shown in Fig. 8. The simulation and experiments showed that a successful PHP should be constructed with $d < 2.5$ mm to allow for ammonia to be used as working fluid and the PHP could be used for the battery thermal management with well design.

4.5. PCMs for thermal management

An ideal thermal management system should be able to maintain the battery pack at an optimum temperature with low volume, weight and cost added. Thermal management systems such as forced air-cooling and liquid-cooling make the overall system too bulky, complex and expensive in terms of blower, fans, pumps, pipes and other accessories [117]. Therefore, for others thermal

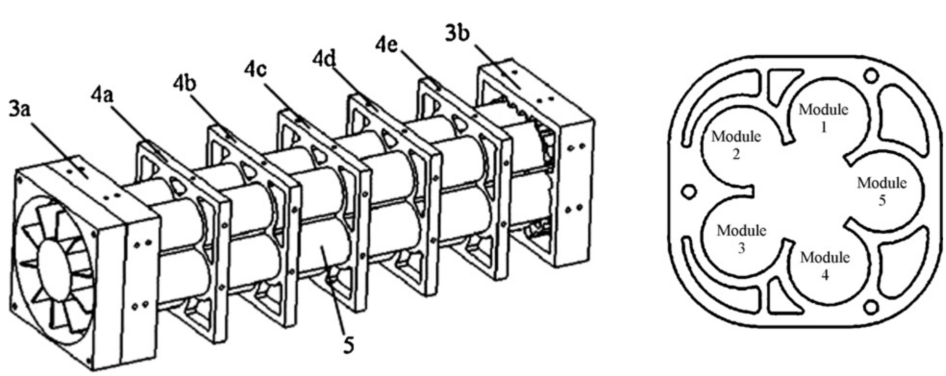


Fig. 6. Structure of cinquefoil battery pack.

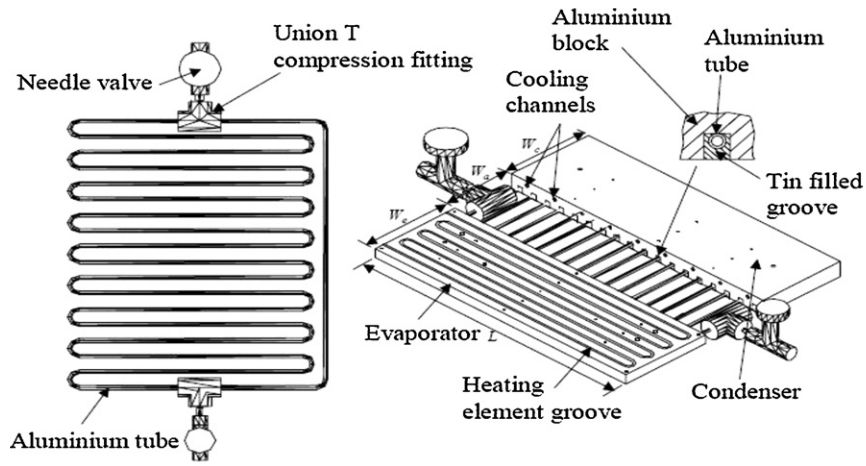


Fig. 7. Aluminum closed loop PHP (4.76 m OD, 3.34 mm ID) [180].

management solutions are required. A novel solution using PCM for battery thermal energy management was proposed for electric and hybrid electric vehicle applications. PCM battery management system, first demonstrated by Al-Hallaj and Selman [181] and patented by Al-Hallaj and Selman [182], performed better than the conventional thermal management system.

In the PCMs battery thermal management, the mass of the PCM required is calculated as follows:

$$M_{PCM} = \frac{Q_{dis}}{C_p(T_m - T_i) + H} \tag{3}$$

where, Q_{dis} (J) is heat of battery release; M_{PCM} (kg) is the quality of PCMs; C_p (J kg^{-1} K^{-1}) is the specific heat of PCMs; T_m (°C) is the temperature of the melting point; T_i (°C) is the initial temperature of PCMs; H (J kg^{-1}) is the phase change latent heat of PCMs.

Mills and Al-Hallaj [183] designed a PCM thermal management system and simulated for laptop battery pack using the entropy coefficient method. Their results showed that PCM significantly improved the performance of the system and kept the operating temperature lower than 55 °C even at the high discharge rate. Selman and Al-Hallaj [155] reported their laboratory test results of a Li-ion battery designed for electric scooter application with four different modes of heat dissipation: (i) natural convection cooling; (ii) presence of aluminum foam heat transfer matrix; (iii) use of phase change material; (iv) combination of aluminum foam and PCM. Their experiment showed that the method (iv) obtained the best effect and from the comparative data they also suggested the future work of the PCM conductivity. The PCM offers safety under stressed conditions considering the conduction and absorption of heat. Kizilel et al. [184] confirmed the validity of using PCM for high-energy Li-ion packs thermal management system at normal and stressed operating conditions by experimental data. One year later a compact type 18650-cell module (4S5P) using the PCM thermal management system over active cooling was demonstrated also in their study [151]. They indicated the possibility to achieve uniform temperature under normal and stressed conditions if the passive thermal management system is used. Sabbah et al. [25] compared the effectiveness of PCM to air forced cooling by numerical simulation and experiment, showed that PCM cooling could keep temperature below 55 °C at constant discharge rate at 6.67C (10 A/cell). In our previous work, we designed a battery thermal management system combined PCM cooling with air cooling; it can be seen in Ref. [185]. Rao et al. [186,187] investigated the composite PCMs with high conductivity used for heat dissipation in cylindrical Ni-MH (SC-Ni-MH, 2200 mA h, 22 mm diameter and 42.5 mm high) and Li-ion rectangle batteries ($LiFePO_4$, 7 A h, 118 mm length, 63 mm width and 13 mm high) at high discharge currents, their experiments further confirmed the previous work.

For low temperature operating, actually, in the Ref. [181], they predicted that PCM is an important advantage for EVs operation under cold conditions or in space applications where the battery temperature drops significantly. Because of the heat stored as latent heat just a smaller part of it is transferred to the surroundings. The stored heat will be rejected to the module when the battery temperature is dropping below the melting point of the PCM.

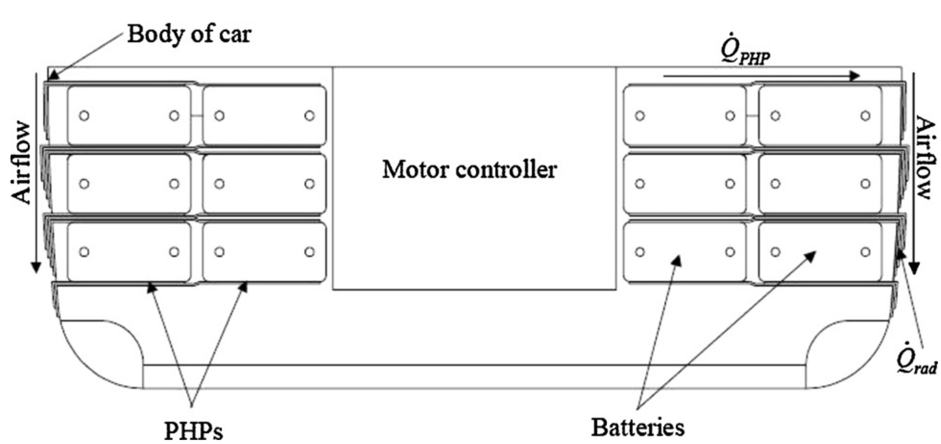


Fig. 8. Schematics of the PHP used in the HEV [180].

Table 14
Trade–off analysis of the battery thermal management.

	Air forced	Liquid	Heat pipe	PCM	Thermoelectric	Cold plate
Ease of use	Easy	Difficult	Moderate	Easy	Moderate	Moderate
Integration	Easy	Difficult	Moderate	Easy	Moderate	Moderate
Efficiency	Low	High	High	High	Low	Medium
Temperature drop	Small	Large	Large	Large	Medium	Medium
Temperature distribute	Uneven	Even	Moderate	Even	Moderate	Moderate
Maintenance	Easy	Difficult	Moderate	Easy	Difficult	Moderate
Life	≥20 years	3–5 years	≥20 years	≥20 years	1–3 years	≥20 years
First cost	Low	High	High	Moderate	High	High
Annual cost	Low	High	Moderate	Low	High	Moderate

Table 15
Thermophysical properties of PCMs.

Compound	Melting point (°C)	Latent heat (kJ/kg)	Thermal conductivity (W/mK)
GR25	23.2–24.1	45.3	–
RT25–RT30	26.6	232.0	0.18 (liquid) 0.19 (solid)
n-Octadecane	27.7	243.5	0.148 (liquid) 0.19 (solid)
$CaCl_2{\cdot}6H_2O$	29.9	187	0.53 (liquid) 1.09 (solid)
$Na_2SO_4{\cdot}10H_2O$	32,39	180	0.15 (liquid) 0.3(solid)
Paraffin wax	32–32.1	251	0.514 (solid) 0.224 (liquid)
Capric acid	32	152.7	0.153 (liquid)
(PEG900)	34	150.5	0.188 (liquid) 0.188 (solid)
Lauric-palmitic	35.2	166.3	–
Lauric acid	41–43	211.6	1.6
Stearic acid	41–43	211.6	1.60 (solid)
Medicinal paraffin	40–44	146	2.1 (liquid) 0.5 (solid)
Paraffin wax	40–53	–	–
P116-Wax	46.7–50	209	0.277 (liquid) 0.140 (solid)

Cosley and Garcia [188] made a trade-off analysis of the different battery thermal management system in 2004. Base on the research in recent years, a more comprehensive of trade-off analysis of the battery thermal management is shown in Table 14. The thermoelectric cooling, confirmed low coefficient of performance, was not recommended to use in battery thermal management. The cold plate, directly contacted with the battery wall with a high thermal resistance, was not recommended.

4.6. PEMFC thermal energy management

The performance of a PEMFC depends obviously on the amount of water vapor, while the local dehydration or water condensation due to uneven temperature distribution can cause performance degradation [26]. There is a moderate temperature range within which the PEMFCs can operate well and reliably. One of the challenges of the PEMFCs for high-power applications is the thermal management. PEMFCs require thermal management not only to maintain a proper operating temperature but also to manage the temperature distribution within the fuel cell [26]. A well designed thermal management, as well as Ni-MH and Li-ion batteries, is very important in electrical vehicles operating. A detailed review of challenges and opportunities of thermal management issues related to PEMFCs technology and modeling can be seen in Ref. [189], which published in 2005. In Ref. [189], Faghri and Guo have revealed challenges and opportunities of thermal management issues related to low temperature fuel cells and high temperature fuel cells, and provide an overview of fuel cell models developed in the past few years before 2005. In this paper, we focus on reviewing the related work published from 2006 to present.

Table 16
Thermal properties of straight-chain alkanes paraffin.

Formula	Molecular weight (g/mol)	Melting point (°C)	Latent heat (kJ/kg)
$C_{17}H_{36}$	240	21.7	213
$C_{18}H_{38}$	254	28.0	244
$C_{19}H_{40}$	268	32.0	222
$C_{20}H_{42}$	282	36.7	246
$C_{21}H_{44}$	296	40.2	200
$C_{22}H_{46}$	310	44.0	249
$C_{23}H_{48}$	324	47.5	232
$C_{24}H_{50}$	338	50.6	255
$C_{25}H_{52}$	352	49.4	238

Matamoros and Bruggemann [143] developed a non-isothermal, three-dimensional numerical model of a PEMFC to compute the water and heat management; their results showed that there may be severe mass transfer limitations depending on the design or water management, temperature plays an important role in the cathode reaction rate of the cell and in the dehydration of the polymer membrane. Dumercy et al. [150] described a 3D thermal modeling by a nodes network model for two PEMFC of 150 and 500 W (respectively, 3 and 20 cells), to predict internal temperatures reached for different functioning configurations; the modeling was validated with different input temperatures of water (without load) and with different loads ranging from 0.3 to 0.5 A cm^{-2}. Bao et al. [144] proposed a methodology, including two compact heat exchangers, radiator, condenser and influence of non-condensable gas, with a steady-state, one-dimensional, isothermal fuel cell and a simple channel-groove pressure drop mode; the mode combining the anode recycling and membrane humidification could get better performance. Zong et al. [145] developed a non-isothermal, non-isobaric water and thermal management model with phase change to simulate the mass and energy transfer processes with a non-uniform stack temperature; the results showed that increasing the flow inlet temperatures is an approach to overcome the water starvation problem and decreasing the cooling temperature is helpful in improving the PEMFC performance. Ahmedem et al. [148] employed a three-dimensional, non-isothermal model with a single straight channel, including humidification and phase transportation; the total water and thermal management for systems operated at high current densities; the results showed that both the in-plane and through-plane permeabilities were affecting water and thermal management, especially in the low permeability ranges, and the numerical results

suggested that modeling with isotropic permeability conditions may overpredict the cell performance, and inaccurately predict the water and thermal management. Yu and Jung [26] developed a thermal model of a PEMFC and a thermal management system, a water transport model, an agglomerate structure electrochemistry model and a two-dimensional heat transfer model, for cells with large active cell areas. Cheong et al. [149] analyzed the water and thermal management with coolant operating conditions for a proton exchange membrane fuel cell, and concluded that to obtain a optimum voltage efficiency of the cell stack, the relative humidity at the H_2 inlet and the heat removal rate was 50% and 0.40–0.65 W/cm^2 cell, respectively. Hu et al. [190] presented a coolant circuit modeling method and a temperature fuzzy control strategy to keep the PEMFC within the ideal operation temperature range, the simulation results demonstrated that the incremental fuzzy controller with integrator can effectively control the PEMFC temperature and the inlet coolant temperature within their objective working ranges respectively. Wen et al. [191] experimentally investigated the effects of the pyrolytic graphite sheets (PGS) on the performance and thermal management of a PEMFC stack. They constructed a PEMFC stack with an active area of 100 cm^2 and 10 cells in series and the results demonstrated the feasibility of application of PGS to the thermal management of a small-to-medium-sized cell stack.

Kwon et al. [192] used a controlled amount of phosphoric acid (PA) in a membrane-electrode assembly which was operated at 150 °C without humidification to maximize high temperature performance of the PEMFCs. Jung et al. [193] revealed that the presence of nano-silicate particles in poly (tetrafluoroethylene)/Nafion/silicate (PNS) membrane enhanced the water uptake at high cell temperature and lowed gas humidity and also reduced the water loss due to electro-osmosis at high current densities. Li et al. [194] prepared a high conductivity $C_{s2.5}H_{0.5}PM_{o12}O_{40}$ (C_sPOM)/polybenzimidazole (PBI) composite for PEFCs operating at high temperature. Wen et al. [195] prepared a series of sulfonated poly (ether sulfone) (SPES)/boron phosphate (BPO_4) composite membranes prepared by a sol–gel method using tripropyl borate and phosphoric acid as precursors for PEMFCs applying at high temperature. Sawada et al. [196] investigated thermal properties of crosslinked-polytetrafluoroethylene films for PEMFCs applications. Bhadra et al. [197] synthesized hyperbranched poly (benzimidazole-co-benzene) with honeycomb structure as a membrane for PEMFCs application in high-temperature. Park et al. [198] constructed a PEMFC based on triazoles attached onto SBA-15 type mesoporous silica; the results showed the proton conductivity of 8.52×10^{-4} S/cm at low humidity of ~10% and 140 °C and exhibited a thermal stability up to 200 °C. Hwang et al. [199] even developed and implemented a heat recovery unit in a PEMFC, the results showed that up to 50% fuel energy can be recovered thermally in the system.

5. Battery thermal management PCMs

5.1. Classification of PCMs based on melting temperature range

Based on above reviews, we learnt that the battery thermal management using PCM confirmed a better performance not only for heat dissipation but also for heating in cold environment. The thermal energy is stored as sensible and latent heat in the PCM, in which the major proportion is latent heat because of high latent heat storage capacity. Latent heat storage is the heat absorption or release when PCM changes from solid to liquid or liquid to gas or vice versa at more or less constant temperature.

There are many PCMs available in any required temperature range. Classification of PCMs can be seen in Refs. [200–202]. Generally, the PCM can be divided into organic, inorganic and eutectic. The study of PCMs was pioneered by Telkes and Raymond in the 1940s but did not receive much attention until late 1970s and early 1980s because of the energy crisis. Agyenim et al. [200] and Sharma et al. [201] reviewed the development of various PCMs. Dutil et al. [203] reviewed the mathematical modeling and simulations based on the first law and on the second law of thermodynamics of the PCMs. Jegadheeswaran and Pohekar [204] reviewed the progress of various PCMs performance enhancement in latent heat thermal storage system. Kenisarin [205] particularly reviewed the investigations and developments of high-temperature PCMs. Almost all the researchers agree that the use of a latent heat storage system using PCMs is an effective way of storing thermal energy.

5.2. PCMs selection for battery thermal management

Proper PCM is a key factor in accessing effective thermal management performance, whether heating or cooling. The main criteria of selection the PCM for battery thermal management are:

(i) Melting point in the desired operating temperature range.
(ii) High latent heat, high specific heat and high thermal conductivity.
(iii) Small volume changes during phase transition.
(iv) Little or no subcooling during freezing.
(v) Stability, non-poisonous, non-flammable and non-explosive.
(vi) Available in large quantities at low cost.

At first, the selection of an appropriate PCM for battery thermal management requires the PCM to have proper melting temperature range. According to the previously mentioned factors, the best range of operating temperature for lead acid, Ni-MH and Li-ion batteries is between 25 and 40 °C. Agyenim et al. [200] summarized the thermophysical properties of PCMs investigated for different applications, the melting temperature range between 20 and 50 °C is extracted and shown in Table 15.

Paraffin wax consists of a mixture of mostly straight chain n-alkanes CH_3–(CH_2)–CH_3. They are chemically inert and stable below 500 °C, show little volume changes on melting and have low vapor pressure in the melt form [201]. For these properties of the paraffin, battery thermal management system with paraffin as PCM may be considered. The thermal properties of straight-chain alkanes paraffin is shown in Table 16 [201].

5.3. Heat transfer enhancement

The traditional PCMs, such as paraffin, were taken as the most promising because of large latent heat, nontoxic, not corrosive, stable and low cost. However, pure paraffin suffers from a low thermal conductivity. High thermal conductivity PCM is demand strongly in battery thermal management. A single PCM is not sufficient for high heat fluxes, while composite materials have been widely used such as insert a metal matrix into the paraffin. To resolve the conflict between large heat storage capacity and low thermal conductivity of traditional materials, composite PCMs were selected. There are many methods have been investigated for increasing the thermal conductivity of PCMs. Some researches discussed the thermal performance of various PCMs in battery thermal management system, the ideal PCMs can be used for battery thermal management summarized in Table 17.

To enhance the thermal conductivity of paraffin, many materials with high thermal conductivity were added into paraffin without used in battery thermal management. The thermal properties of these paraffin based composites PCMs are summarized in Table 18. The thermal conductivity of the composite PCMs was obviously higher than that of the pure paraffin owing to the additives.

Table 17
Ideal PCMs in battery thermal management.

Reference	Method	PCMs	K (W/m^2 K)	Latent heat (kJ/kg)	Melting range (°C)	Specific heat (kJ/kg K)
[117]	Simulation	PW	0.21/0.29	195	40–44	1.77
[155]	Experiment Simulation	PCM/AF	–	–	–	–
[206]	Experiment Simulation	PW	0.12/0.21	173.4	46–48	289
[151]	Simulation	PW/graphite	16.6	123	42–45	1.98
[25]	Simulation	PCM/graphite	16.6	181	52–55	1.98
[184]	Simulation	PCM/graphite	16.6	185	42–45	1.98
[183]	Simulation	PCM/EG	16.6	127		1.98
[207]	Experiment	PCM/EG	4–26	–	~55	–
[27]	Experiment	PCM/EG	14.5(12 h)	–	–	–

EG: expanded graphite; AF: aluminum foam; PW: paraffin wax.

5.4. Thermo-mechanical behaviors of PCMs

Although many thermal properties of PCMs for battery thermal management are discussed, very little results are available about mechanical properties of these materials. On one side, it is important to get higher thermal conductive materials, but on the other side, it is also important to get a stable and stronger battery module to withstand thermo-mechanical effects while in operation [27]. In the previous literatures, only Alrashdan et al. performed a systematic experimental study to analyze the important effects of the thermo-mechanical properties including thermal conductivity, tensile compression and bursting, on prepared paraf-

Table 18
Thermal properties of paraffin based composites PCMs.

Reference	PCMs	K (W m^2/K)	Latent heat (kJ/kg)	Melting T_m (°C)
[208]	Paraffin/HDPE–EVA/OMT: (1) 75%/25%/0 (2) 75%/2.5%/22.5% (3) 75%/5%/20% (4) 75%/10%/15%	–	(1) 111.52 (2) 99.78 (3) 97.21 (4) 91.66	(1) 57.65 (2) 57.92 (3) 57.13 (4) 57.33
[209]	Paraffin75%/PSC25%	(1) 0.387	(1)165.16	(1) 56.3
[210]	Paraffin/Al_2O_3: (1) 95%/5% (2) 90%/10%	–	(1) 225.6 (2) 212.3	(1) 26.0 (2) 26.3
[211]	Paraffin/Aluminum (1) –	(1) 4.09	(1) 266	(1) 53.5
[212]	Paraffin/HDPE/APM/EG: (1) 60%/40%/0/0 (2) 60%/20%/20%/0 (3) 60%/15%/25%/0 (4) 60%/20%/15%/5% (5) 60%/15%/20%/5%	(1) 0.28 (2) 0.29 (3) 0.34 (4) 0.51 (5) 0.85	(1) 68.3 (2) 74.7 (3) 81.5 (4) 68.8 (5) 73.6	(1) 51.59 (2) 50.58 (3) 51.70 (4) 51.10 (5) 50.58
[213]	Paraffin/HDPE/EG/APP: (1) 60%/15%/2%/23% (2) 60%/15%/4%/21%	–	(1) 91.23 (2) 90.89	(1) 56.01 (2) 56.31
[214]	Paraffin/HDPE/EG/APP/ZB (1) 60%/40%/0/0/0 (2) 60%/20%/20%/0/0 (3) 60%/20%/10%/10%/0 (4) 60%/20%/10%/0/10%	–	(1) 78.78 (2) 99.98 (3) 93.84 (4) 91.21	(1) 55.25 (2) 55.74 (3) 55.43 (4) 55.24
[215]	Paraffin/EG: (1) 98%/2% (2) 96%/4% (3) 93%/7% (4) 90%/10%	(1) 0.40 (2) 0.52 (3) 0.68 (4) 0.82	(1) 192.6 (2) 188.0 (3) 181.9 (4) 178.3	(1) 41.1 (2) 41.0 (3) 40.7 (4) 40.2
[216]	Paraffin/MWNTs (1) 99.8%/0.2% (2) 99.5%/0.5% (3) 99.0%/1.0% (4) 98.0%/2.0%	–	(1) 165.4 (2) 165.1 (3) 164.9 (4) 163.8	(1) 52.9 (2) 52.7 (3) 52.5 (4) 52.0
[217]	Paraffin/graphite: (1) 95%/5% (2) 90%/10% (3) 85%/15% (4) 80%/20%	(1) 0.204 (2) 0.229 (3) 0.310 (4) 0.482	–	–
[218]	Paraffin–HDPE/EG: (1) 99%/1% (2) 98%/2% (3) 97%/3% (4) 96%/4% (5) 96.4%/4.6%	(1) 0.58 (2) 0.76 (3) 1.03 (4) 1.25 (5) 1.36	–	–

HDPE-EVA/OMT: polyethylene/poly (ethylene-co-vinylacetate)/organophilic montmorillonite; PSC: porous silica ceramic; HDPE: high-density polyethylene; APM: ammonium polyphosphate (APP), pentaerythritol (PER) and melamine (MA); APP: ammonium polyphosphate; ZB: zinc borate; MWNTs: multi-walled carbon nanotubes; Paraffin-HDPE: 80% + 20%.

Table 19
Thermo-mechanical behaviors of PCMs with different impregnation times.

Property	Specification				
	12 h	9 h	6 h	3 h	1 h
Thermal conductivity (W/mK)	14.5	14.3	14.1	13.6	13.0
Bulk density of composite (kg/m^3)	789	775.4	766.3	660.4	622.5
Bulk density of graphite (kg/m^3)	210	210	210	210	210
Tensile strength (22 °C) (kPa)	1040	1060	1072	1100	892
Tensile strength (45 °C) (kPa)	196	186	194	260	264
Compressive strength (22 °C) (kPa)	2571	2546	2394	2317	2292
Compressive strength (45 °C) (kPa)	292	280	280	267	241
Bursting strength (22 °C) (MPa)	650	630	600	560	530
Bursting strength (45 °C) (MPa)	110	130	140	140	160

fin wax/expanded graphite composite PCMs for Li-ion batteries and. The thermo-mechanical behaviors of the PCMs with different impregnation times of their study are shown in Table 19 [27]. Their experiment results showed that with the percentage of paraffin wax increasing in the composite PCMs, both tensile and compressive strengths were increased at room temperature, but become weaker at relatively elevated temperatures, whereas the burst strength increased at room temperature. The experiment plays a positive role in the development of battery thermal management. However, there is a lot of works need to be further investigated.

6. Conclusion

It has been observed that the EVs, HEVs and FCEVs are effective to reduce GHG and pollutants emission and save energy. The high energy power batteries, such as Ni-MH as a short and medium-term selection, Li-ion batteries as medium-term and fuel cells as long-term selection, can be seen as the best choice of the future for application in clean vehicles. The battery thermal energy management is very important to enhance the battery performance, and then to improve the application of electric vehicles. Numerical models and simulation are positive to analyse the battery thermal behavior. Traditional battery thermal energy management, such as air and liquid, make the overall system too bulky, complex and expensive in terms of blower, fans, pumps, pipes and other accessories. A novel method with pulsating heat pipe may be more effective with well designed. At stressful and abuse conditions, especially at high discharge rates and at high operating or ambient temperatures, PCMs for thermal management will be a better selection. Nevertheless, the conflict between large heat storage capacity and low thermal conductivity of traditional materials must be solved, and the thermal character of the composite materials should use in battery management system and investigate experimentally. More work on thermo-mechanical behaviors of PCMs and system need to be done further. Finally, many experiments and simulations are focused primarily on the heat dissipation, the possibility of the heat collection and recycling need discuss in term of energy saving and efficient. Besides, it is difficult to develop new high temperature materials for battery preparation but is worth if it is accomplished.

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